AFRL-AFOSR-VA-TR-2015-0345

(MICRO-AND NANO-OPTOMECHANICAL DEVICES FOR SENSORS, OSCILLATORS, AND PHOTONICS

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10/26/2015
Final Report

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
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Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
26-10-2015

2. REPORT TYPE
Final Performance

3. DATES COVERED *(From - To)*
10-06-2010 to 09-06-2015

4. TITLE AND SUBTITLE
MICRO-AND NANO-OPTOMECHANICAL DEVICES FOR SENSORS, OSCILLATORS, AND PHOTONICS

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-10-1-0284

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
Oskar Painter

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
CALIFORNIA INSTITUTE OF TECHNOLOGY
1200 E. CALIFORNIA BLDV
PASADENA, CA 91125 US

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF Office of Scientific Research
875 N. Randolph St. Room 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/AFOSR RTB1

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
A DISTRIBUTION UNLIMITED: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Our efforts within the DARPA/MTO ORCHID program focused on developing and entirely new class of micro- and nano-scale optomechanical devices in which large coupling between light and mechanical motion could be realized via radiation pressure. Application of these devices to mechanical sensors, microwave signal synthesis, and microwave photonics were explored.

15. SUBJECT TERMS
AND, PHOTONICS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Oskar Painter
Unclassified	Unclassified	Unclassified	UU		19b. TELEPHONE NUMBER *(Include area code)* 626-395-8008

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Grant Summary Report

Sponsor: DARPA/Air Force Office of Scientific Research
Sponsor Award Number: FA9550-10-1-0284
Award Title: Micro- and Nano-Optomechanical Devices for Sensors, Oscillators, and Photonics
Award Period: 10-JUN-2010 – 09-JUN-2015
Principal Investigator: Prof. Oskar Painter, California Institute of Technology (CIT)
co-Principal Investigators: Prof. Kerry Vahala (CIT), Prof. Jeff Kimble (CIT), Prof. Tobias Kippenberg (EPFL)
Report Prepared by: Prof. Oskar Painter (CIT)

Abstract: Our efforts within the DARPA/MTO ORCHID program focused on developing and entirely new class of micro- and nano-scale optomechanical devices in which large coupling between light and mechanical motion could be realized via radiation pressure. Application of these devices to mechanical sensors, microwave signal synthesis, and microwave photonics were explored.

Summary of Key Findings and Research Activities:

Our efforts within the ORCHID program were quite diverse, spanning several different device geometries (optomechanical crystals, whispering gallery resonators, and Fabry-Perot resonators) and application areas (optical cooling and low-noise mechanical transducers, low-noise optomechanical oscillators and microwave signal synthesis, and atom-photon-phonon optomechanics). Below we provide a summary of the key findings and "lessons learned" from our research efforts over the course of the ORCHID program:

Development of Optomechanical Crystals: Optomechanical crystals (OMCs) are engineered crystals formed from patterning a bulk material with dielectric and elastic properties, resulting in strong dispersion and interaction between optical and acoustic waves with wavelengths on the scale of the patterning. Thin-film OMCs, which were the focus of our work in ORCHID, are formed from the patterning of an optically thin (~ wavelength λ) top device layer which is released from the underlying substrate, and can be fabricated using conventional lithography and plasma etching techniques. We developed a 1D nanobeam OMC cavity with extremely large radiation pressure coupling between light in the 1500nm band and acoustic waves in 3-6 GHz band (see Pub. [19]). The radiation pressure or optomechanical coupling is quantified by the vacuum coupling rate, g_0, which physically represents the shift in the optical cavity resonance frequency for mechanical motion at the scale of the quantum zero-point amplitude, x_{ZPF}. The important figure of merit for classifying the performance of all cavity-optomechanical devices is the ratio g_0/κ, where κ is the optical resonance linewidth. $g_0/\kappa > 1$ corresponds to a regime in which interactions between single photons and single phonons can be resolved (see Pub. [16]). The nanobeam OMC we realized has a $g_0/\kappa = 0.0069$, which is the highest reported to date for a solid-state system. An

important aspect of the nanobeam design was the incorporation of bulk elasto-optic effects. Previous work had focused solely on the moving boundary contribution, which is a surface effect, to the optomechanical coupling. The bulk elasto-optic effect of silicon in our devices was found to contribute roughly 90% of the optomechanical coupling. We also found that elasto-optic and moving boundary effects can cancel each other in nanoscale photonic waveguides or resonators, indicating that both components should be considered during the design phase.

Laser cooling of mechanical motion to the quantum ground state: Utilizing the optimized 1D nanobeam OMC device describe above we demonstrated for the first time the laser cooling of a mechanical resonator to its quantum ground state of motion (phonon occupancy < 1). This demonstration, presented in Pub. [9], required cryogenic pre-cooling to ~10K to reduce the mechanical damping of the 3.5 GHz acoustic resonance. Laser cooling to the ground state in a room temperature environment would have been possible in these devices if the mechanical damping were lower at room temperature in silicon, and we note that for this purpose other materials such as SiC or diamond with lower thermo-elastic damping may be preferred. See also laser cooling work with microtoroids in Pub. [8,13].

Electromagnatically-Induced Transparency in a Cavity-Optomechanical Resonator: In Pub. [6] we utilized the radiation pressure interaction between optical and acoustic waves in the 1D nanobeam OMC to realize a form of electromagnetically-induced transparency (EIT), also referred to as optomechanically-induced transparency (OMIT). In this work we showed that EIT phenomena in optomechanical devices could be used to tunably advance or delay the propagation of light by times of order ~1 μs in a device of footprint ~5 μm. This result highlights the fact that optomechanical devices can be used not only to optically manipulate or detect mechanical motion, but also as a means to perform mechanical manipulation of optical signals. Further ideas along this line are explored theoretically in Pub. [3,4].

Sideband Asymmetry Thermometry: In Pub. [11,20,21] we explored a new method for optical sensing of mechanical motion using a 1D nanobeam OMC. Using quantum asymmetry between phonon absorption and emission processes, we demonstrated the *absolute* calibration of the mode occupancy/temperature of a mechanical resonator. The "calibration" is referenced only to the vacuum zero-point noise level. The caveat is that this measurement only works effectively at phonon occupancies close to unity. Pub. [20,21] explore the sensitivity of this technique to parasitic laser noise, and clear up a long standing misconception of the role of mechanical zero-point noise in limiting the precision of a displacement or force sensor.

Ponderomotive Squeezing of Light on a Chip: In Pub. [25] we reported on the first demonstration of ponderomotive squeezing of light in a solid-state mechanical system (similar prior work had been performed in an atomic gas). We showed that modest squeezing of ~5% below the standard quantum limit (vacuum noise level) in a silicon double-nanobeam OMC. Squeezing was obtained over a ~5 MHz bandwidth centered close to the mechanical resonance at 30 MHz, even in the presence of substantial thermal noise. Squeezing in this case was limited by the low mechanical Q-factor. With straightforward improvements in the mechanical design to reduce the clamping loss of the double-nanobeam, we predict that squeezing at the 8dB could be realized in the optical output field of the OMC. An interesting follow-up to this work would be to feed the squeezed

output of one device into the input of a second device, thus realizing a fully on-chip mechanical sensor with reduced shot noise limit.

Simultaneous Photonic and Phononic Bandgap Optomechanical Crystals: In Pub. [1] we developed the design methodology and blueprints for realizing thin-film optomechanical crystals (OMCs) with simultaneous photonic and phononic bandgaps (dubbed "snowflake" crystals due to the snowflake-like geometry of their unit cell). These optomechanical crystals can be used to form optomechanical circuits in which near-infrared (1500nm) light and microwave (GHz) acoustic waves are simultaneously, and independently routed in the plane of a microchip. Co-resonant cavities can also be formed in which the optical and acoustic fields interact strongly. Such circuits can be readily adapted to wafer formats such as silicon-on-insulator (SOI) or GaAs/AlGaAs.

X-band Optomechanical Oscillator: In Pub. [32] we successfully realized a snowflake OMC cavity in SOI, demonstrating an X-band (10 GHz) optically-driven mechanical oscillator. Notably, the optical power handling capability of the snowflake structure is significantly improved (x10) compared to the 1D nanobeam OMCs we had previously demonstrated due to the 2D connectivity of the snowflake crystal. We also found that the current snowflake cavity designs are extremely sensitive to small perturbations in their geometry, resulting in localization of acoustic waves to ~10nm fabrication defects in the structure. This should be a relatively simple fix in future designs. Future design work should also address whether larger optomechanical coupling can be realized in snowflake or snowflake-like OMCs. Current designs realize an optomechanical coupling coefficient of $g_0/2\pi$ = 250kHz, which is roughly 4 times lower than in optimized 1D nanobeam structures. If the optomechanical coupling could be further increased along these lines, it could enable much higher frequency mechanics (K-band) to be addressed.

Optomechanical Crystal Circuits for Microwave Signal Processing: In Pub. [46] we have realized small OMC circuits on SOI which incorporate optomechanical cavities coupled together via optical and phononic waveguides. These circuits are used to demonstrate the filtering and delay of microwave signals encoded on a 1550nm optical carrier. In particular, we show it is possible to realize very narrowband microwave filters (17kHz) and long microwave delay lines (13 μs) with these OMC circuits. The filer/delay properties are tunable with an optical control signal. Also noteworthy, is the realization of "distant mechanical coupling" in which virtual phonon excitations of a phonon waveguide couple together two spatially separated mechanical resonators. One could use this phenomena to perhaps create mechanical sensors capable of operating in harsh environments, in which the mechanical sensing is perfomed in a separate location from the (optical) read-out of the sensor. Challenges for creating more complex and functional OMC circuits involve overcoming fabrication non-uniformity and variability which results in the detuning of resonant optical and mechanical cavities at different points in the circuit. Future work in this direction should likely look at realizing more robust OMC circuit implementations, either through post-process tuning or incorporating dynamic tuning methods of optical and mechanical cavities.

Microwave Synthesis using an On-Chip Brillouin Oscillator: In publications [18,28] we describe the development of ultra-high-Q planar silica-on-silicon disk resonators for realizing Stimulated Brillouin Scattering (SBS) oscillators. The size of the disk resonator (~6mm) is carefully designed

such that the free spectral range of the cavity matches the Brillouin gain shift of silica. Key to the resonator fabrication is the ability to use standard optical lithography processes to define the device geometry, as opposed to previous high-*Q* silica resonators that utilized reflow.

In Pub. [23] we report the application of cascaded Brillouin oscillation to microwave frequency synthesis at a level comparable to mid-range commercial, all-electrical synthesizers. Although fibre-based Brillouin lasers have been studied for microwave generation, the present device is the first chip-based Brillouin microwave source. Moreover, the device has a record low-whitephase-noise floor (-160 dBc Hz^{-1}) for any microcavity-based microwave source (even including non-Brillouin-based methods). It can also generate coherent microwave power in excess of 1mW without any optical or radio frequency (RF) amplification, a significant simplification as it eliminates the need for microwave amplification stages after the photodetector. Moreover, being chip based devices, the current sources offer integration opportunities for control and additional functions.

By operating the Brillouin at shorter pump wavelengths or by operating on higher-order Stokes lines, the base frequency of the synthesizer can be readily boosted. For example, by operation with a green pump (doubled yttrium aluminum garnet laser), the base frequency would be boosted to beyond 60GHz using the same Stokes 1 to Stokes 3 photomixing configuration demonstrated in Pub. [23] (again with no degradation in phase-noise performance). Also, by operation on the 1–5 or 1–7 Stokes combinations, millimeter-wave generation well beyond 100GHz is feasible. Likewise, electronic dividers have been demonstrated to these frequencies, thereby making the possibility of high-performance millimeter-wave synthesizers possible using this approach. It is important to note that such millimeter-wave synthesizers would be predicted to produce X-band signals with significantly lower phase noise than what has even been demonstrated in Pub. [23]. This is because the divider process quadratically improves the phase noise. For example, by only maintaining the Schawlow–Townes noise at shorter pump wavelengths, the predicted X-band (~10GHz) phase-noise level would be -130 dBc Hz^{-1} at 100 kHz offset upon division of a 90-GHz SBS-generated base frequency. Ultimately, the current limit to phase noise in these devices is the onset of cascade to higher-order Stokes lines. If this process could be forestalled through, for example, judicious cavity dispersion control, then much lower phase-noise levels than what has been demonstrated here are possible.

Electro-optical frequency division and stable microwave synthesis: In publication [36] we present a way to generate high-performance microwave signals through optical frequency division (OFD) by using a cascade of direct phase modulation and self-phase modulation to create an optical comb. Because the spectral line spacing is set by the electrical oscillator used to drive the phase modulators (as opposed to an optical resonator), the method of microwave synthesis has similarities to conventional microwave synthesizers while also leveraging the power of OFD so as to reduce phase noise.

In our approach, two laser lines having good relative frequency stability provide an optical reference for the microwave source. These laser lines are produced by Brillouin oscillation in a single high-quality-factor (Q) microcavity. However, the lines could also result from any stable optical references, including various types of dual-mode lasers, two lasers locked to distinct optical

modes of a reference cavity, or lasers stabilized to atomic transitions. The laser lines enter the frequency divider portion of the signal generator, where they are phase modulated by a pair of modulators at a frequency set by a voltage-controlled electrical oscillator (VCO). The sideband spectrum created by the phase modulators is further broadened through pulse-forming and self-phase modulation in an optical fiber. The comb of lines extending from each laser line results in a pair of sidebands near the midpoint of the frequency span. These are optically filtered and detected. The detected beat-note signal contains the phase noise of the VCO, but magnified by the optical division factor. It therefore provides a suitable error signal for phase-lock loop control of the VCO.

This new photonic architecture for OFD provides a route to improve the phase noise of a common VCO. In the present configuration, dual SBS lasers have been co-generated in a single, chip-based resonator to establish a stable reference as high as 1.61 THz, resulting in a division factor of 148. Resulting phase noise of a 10.89GHz voltage-controlled oscillator (VCO) is lower than an Agilent MXG source at 1kHz offset, and lower than an Agilent PSG source at 10kHz offset. Although dual-pumped SBS laser lines provide an excellent reference frequency, it should also be possible to lock two lasers to a resonator to establish the reference. Because the current frequency separation is limited by the pump lasers, much larger division ratios and potentially lower phase noise levels should be possible. In comparison with conventional OFD by use of a self-referenced frequency comb, this technique does not presently offer as large a division ratio. However, it is simple and relatively low-cost and also provides tuning of the electrical carrier. Moreover, it relies on a reference signal derived from the relative phase of two lasers as opposed to the absolute phase of a single laser. This can potentially improve the robustness with respect to microphonics and other sources of technical noise.

Note that this work has been spun off into an SBIR activity (nominally connected with the DARPA PULSE program), under the supervision of Dr. Prem Kumar. Current activities involve demonstration of a compact, rack-mountable system which will be tested/calibrated at NIST.

Hybrid on-chip optomechanical transducer for ultrasensitive force measurements: In real-time quantum feedback protocols, the record of a continuous measurement is used to stabilize a desired quantum state. Recent years have seen successful applications of these protocols in a variety of well-isolated micro-systems, including microwave photons and superconducting qubits. However, stabilizing the quantum state of a tangibly massive object, such as a mechanical oscillator, remains very challenging: the main obstacle is environmental decoherence, which places stringent requirements on the timescale in which the state must be measured.

In Pub. [45] we describe a position sensor that is capable of resolving the zero-point motion of a solid-state, 4.3-megahertz nanomechanical oscillator in the timescale of its thermal decoherence, a basic requirement for realtime (Markovian) quantum feedback control tasks, such as groundstate preparation. The sensor is based on evanescent optomechanical coupling to a high-Q microcavity, and achieves an imprecision four orders of magnitude below that at the standard quantum limit for a weak continuous position measurement6—a 100-fold improvement over previous reports—while maintaining an imprecision-back-action product that is within a factor of five of the Heisenberg uncertainty limit. As a demonstration of its utility, we use the measurement

as an error signal with which to feedback cool the oscillator. Using radiation pressure as an actuator, the oscillator is cold damped with high efficiency: from a cryogenic-bath temperature

of 4.4 kelvin to an effective value of 1.160.1 milliKelvin, corresponding to a mean phonon number of 5.360.6 (that is, a ground-state probability of 16 per cent).

Collectively, our results establish new benchmarks for the linear measurement and control of a mechanical oscillator. Looking forward, high-efficiency optomechanical sensors may enable a variety of feedback applications such as backaction evasion and mechanical squeezing. One of the primary challenges in further improving the feedback cooling and quantum control of the mechanical resonator in our system is parasitic optical absorption heating. With expected improvements in the optomechanical coupling by moving to a photonic crystal nanobeam cavity, and with further, reasonable, reductions in the optical absorption, it is anticipated that feedback cooling from a room temperature environment to the quantum ground state could be realized.

Optical Trapping and Mechanical-Q Enhancement: The quality factor of a mechanical resonator is an important figure of merit for various sensing applications and for observing quantum behavior. In Pub. [14] (theoretical work) and [15] (experimental work) we describe and demonstrate a novel technique to push the quality factor of a micromechanical resonator beyond conventional material and fabrication limits by using an optical field to stiffen or trap a particular motional mode. Optical forces increase the oscillation frequency by storing most of the mechanical energy in a nearly lossless optical potential, thereby strongly diluting the effect of material dissipation. By placing a 130 nm thick SiO2 pendulum in an optical standing wave, we achieve an increase in the pendulum center-of-mass frequency from 6.2 to 145 kHz. The corresponding quality factor increases 50-fold from its intrinsic value to a final value of $Q = 5.8\text{x}10^5$, representing more than an order of magnitude improvement over the conventional limits of SiO2 for this geometry.

We expect that further significant advances can be made with refined fabrication techniques and a shift to materials with better mechanical characteristics. For instance, the mechanical frequency and the corresponding Q-factor of our trapped pendulum is limited in part by the large suspended annulus to which the tether is attached (see Pub. [15]). Using wet chemical anisotropic etching of Si to release the pendulum, it should be possible to fabricate a device with an annulus less than 10 μm wide. Furthermore, while SiO_2 proved to be convenient to work with initially, it suffers a relatively low intrinsic quality factor of $Q_i = 10^4$ that is likely to be limited by surface-related damping mechanisms. Although the nature of surface damping is still an open question and not necessarily a fundamental limitation, we can still compare our observed Qi to other SiO_2 devices. From the extensive phenomenological study of SiO_2 loss angle and the surface-to-volume ratio of our pendulum, we would expect Q_i=9200, which is consistent with our observation of Q_i=1.1x10^4. Switching platforms to stressed silicon nitride or crystalline silicon should enable material quality factors of $Q_i=10^5$–10^7. In initial experiments with Si_3N_4, for example, we have fabricated stressed, tethered structures with bare frequencies of 172 kHz and Q_i=1.3x10^7. We expect that by applying optical trapping to such structures, final quality factors of $Q_f=10^8$ might be possible for oscillator frequency ~1 MHz. Such values would be unprecedented

for any fabricated nano- or micromechanical system, and remarkably, would be competitive with the prediction for untethered levitated nanoparticles

Our technique holds promise as a tool to reduce the role of mechanical dissipation in a wide variety of sensing applications as well as in the emerging field of quantum optomechanics. Our device can be integrated into a high-finesse cavity employing the ‘‘membrane-in-themiddle’’ geometry, for example, and could provide the long coherence times necessary to observe quantum behaviors (i.e., macroscopic entanglement) in a room temperature environment.

Atom-Photon-Phonon Optomechanics: Localizing arrays of atoms in photonic crystal waveguides (PCW) with strong atom–photon interactions could provide new tools for quantum networks1–3 and enable explorations of quantum many-body physics with engineered atom–photon interactions. Bringing these scientific possibilities to fruition requires creation of an interdisciplinary ‘toolkit’ from atomic physics, quantum optics and nanophotonics for the control, manipulation and interaction of atoms and photons with a complexity and scalability not currently possible. Important initial advances to integrate atomic systems and photonics have been made within the setting of cavity quantum electrodynamics with atom–photon interactions enhanced in micro- and nanoscopic optical cavities and waveguides. At a minimum, the further migration to photonic crystal structures should allow the relevant parameters associated with these paradigms to be pushed to their limits26 and greatly facilitate scaling. For example, modern lithographic processing can create nanoscopic dielectric waveguides and resonators with optical quality factors $Q>10^6$ and with efficient coupling among heterogeneous components.

A more intriguing possibility that has hardly been explored is the emergence of completely new paradigms beyond the cavity and waveguide models, which exploit the tremendous flexibility for modal and dispersion engineering of PCWs. For example, the ability to tune band edges near atomic transition frequencies can give rise to strongly enhanced optical interactions. This enables a single atom to exhibit nearly perfect emission into the guided modes and to act as a highly reflective mirror. The entanglement of photon transport with internal states of a single atom can form the basis for optical quantum information processing with on-chip quantum optical circuits. At the many-body level, the strong interplay between the optical response and large optical forces of many atomic ‘mirrors’ can give rise to interesting optomechanical behaviour, such as self organization.

The prerequisite to all of these possibilities is a designable platform that allows the simultaneous alignment of optical bands for optical trapping and for interaction physics with atoms, which we demonstrate Pubs. [29,33,40,44] for the first time. Specifically, we report advances that provide rudimentary capabilities for such a ‘toolkit’ with atoms coupled to a PCW. We have fabricated the integrated optical circuit with a photonic crystal whose optical bands are aligned with atomic transitions for both trapping and interfacing atoms with guided photons. The quasi-1D PCW incorporates a novel design that has been fabricated in silicon nitride (SiN), and integrated into an apparatus for delivering cold caesium atoms into the near field of the SiN structure. From a series of measurements of reflection spectra with N~1 atoms coupling to the PCW, we infer that the rate of single-atom radiative decay into the waveguide mode is

approximately to spontaneous emission into all other radiation modes. We have also recently measured cooperative atomic effects in the form of superradiance in such structures when N>1.

Through further optimization of our atomic loading and trapping methods, we are confident that we can realize much larger number of atoms (N~100) in the PCW, where the mechanical degree of freedom of the atoms will come into play, realizing a whole new form of optomechanical system. Current challenges involve reducing optical absorption in the PCW so as to allow for higher (mW-level) optical input powers for guided mode trapping, and integrating a protective coating on the PCW to avoid deposition of cesium on the waveguide surface (which leads to unwanted tuning of the optical waveguides, and ultimately, mechanical failure).

Publications:

Details of our research efforts during the ORCHID program are described in our publications, which we do not reproduce here, but rather include at the end of this report. We recommend that these should be read for full comprehension of our work. A complete list of our ORCHID-related publications are also listed below for reference.

We have published **46** peer-reviewed articles on our ORCHID work, a full list of which is given below. These include a Review of Modern Physics article on “Cavity Optomechanics” (Pub. [36]) and a book on the same subject (Pub. [31]). The number of citations accrued by our ORCHID publications according to the Web of Science database (Thomson and Reuters) is at **2,324** as of the writing of this report.

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Attachments: We have attached below a number of our published papers which provide the important details of our research results during the ORCHID program.

ORCHID Theory Team: Final Report

A. A. Clerk, F. Marquardt and P. Meystre

October 5, 2015

Introduction

The theory team supported by the ORCHID program had three principal investigators: Pierre Meystre (University of Arizona), Florian Marquardt (University of Erlangen), and Aashish Clerk (McGill University). The goals for their work in this program had two central thrusts:

- Provide theoretical support for experimental work in quantum optomechanics funded through the ORCHID program.
- Develop new theoretical ideas and experimental protocols to help guide the next generation of experiments in quantum optomechanics.

The theory work supported through ORCHID resulted in over 60 publications, including 15 papers in Physical Review Letters. There were also several successful theory-experiment collaborations, including two papers in Science, a publication in Nature Physics, and papers in Physical Review Letters and Physical Review X.

In what follows, we provide a set of research highlights for each of the three ORCHID theory groups, discussing in each case promising avenues for future work.

Marquardt group highlights

Optomechanics in the single-photon strong coupling regime

- *Full photon statistics of a light beam transmitted through an optomechanical system*, Andreas Kronwald, Max Ludwig, and Florian Marquardt, Phys. Rev. A **87**, 013847 (2013).
- *Optomechanically Induced Transparency in the Nonlinear Quantum Regime*, Andreas Kronwald and Florian Marquardt, Phys. Rev. Lett. **111**, 133601 (2013).
- *Enhanced Quantum Nonlinearities in a Two-Mode Optomechanical System*, Max Ludwig, Amir H. Safavi-Naeini, Oskar Painter and Florian Marquardt, Phys. Rev. Lett. **109**, 063601 (2012)

The most fundamental way of characterizing the strength of the optomechanical interaction is to quantify the optical frequency shift that is induced by a mechanical displacement of the size of the mechanical zero-point fluctuations (typically a femtometer). Right now, that single-photon optomechanical coupling rate is still smaller by at least two orders of magnitude than the photon decay rate, at least in solid-state devices. Nevertheless, it is important to understand the signatures that will eventually be observed when optimization of devices has produced a coupling strength larger than the decay rate. We have worked out the full statistics of photons being transmitted through such an optomechanical system. Moreover, we pointed out how the effect of optomechanically induced transparency could be used as a telltale signature of this regime. We also suggested a way to boost the interactions in situations where a large mechanical frequency would otherwise weaken the effects.

Future studies based on this might explore how such a regime would affect photon transport in lattices.

Engineering photon and phonon transport in optomechanical arrays

- *Optomechanical creation of magnetic fields for photons on a lattice*, M. Schmidt, S. Keßler, V. Peano, O. Painter, F. Marquardt, Optica **2**, 635 (2015).
- *Optomechanical Dirac Physics*, Michael Schmidt, Vittorio Peano, and Florian Marquardt, New J. Phys. **17**, 023025 (2015).
- *Topological Phases of Sound and Light*, Vittorio Peano, Christian Brendel, Michael Schmidt, and Florian Marquardt, Phys. Rev. X **5**, 031011 (2015).

An optomechanical device usually consists of a single optical mode (e.g. a cavity mode in an optical resonator) being coupled to the mechanical displacement of a single vibrational mode. New effects will come into play once this is extended to arrays of many optical and mechanical modes. These can be implemented in many possible platforms (such as disk resonator arrays, as produced by the group of Michal Lipson). However, a particularly promising platform consists in optomechanical crystals, i.e. photonic crystals that feature micron-scale co-localized optical and vibrational modes (as pioneered by the group of Oskar Painter). We have studied the behaviour

of photons and phonons in such arrays. For example, one may exploit the mechanical vibrations to engineer artificial magnetic fields for the photons, forcing them to propagate along edge states of the sort otherwise known from the electronic quantum Hall effect. One can also consider lattices with a bandstructure mimicking that of important electronic materials, like graphene, and study the resulting transport of coupled photon-phonon polaritons on a honeycomb lattice. One particularly intriguing aspect is the ability to engineer the flow of phonons on the micronscale, at will, using suitable light fields. We have proposed an optomechanical implementation of a so-called 'Chern insulator' (a variety of a topological insulator) for sound. If realized, this would be the first example of topologically protected transport of sound waves in the solid state. We are working together with the experimental team of Oskar Painter to at least produce small-scale versions of this.

Synchronization dynamics

- *Photonic Cavity Synchronization of Nanomechanical Oscillators*, M. Bagheri, M. Poot, L. Fan, F. Marquardt, H. X. Tang, Phys. Rev. Lett. **111**, 213902 (2013).
- *Quantum many-body dynamics in optomechanical arrays*, Max Ludwig and Florian Marquardt, Phys. Rev. Lett. **111**, 073603 (2013).
- *Pattern phase diagram for 2D arrays of coupled limit-cycle oscillators*, Roland Lauter, Christian Brendel, Steven J. M. Habraken, and Florian Marquardt, Phys. Rev. E **92**, 012902 (2015).

The nonlinear dynamics of optomechanical devices can give rise to so-called self-induced oscillations. These are self-sustained mechanical oscillations driven by the energy input provided by the incoming laser radiation. In the past, we have pointed out that two such optomechanical limit-cycle oscillators can synchronize, which could be important for technical applications, as it reduces the system's sensitivity to noise. We have worked together with the group of Hong Tang in their realization of such a system of two synchronizing oscillators. We have analyzed theoretically how a full array of coupled optomechanical oscillators can give rise to a synchronization transition driven by the competition between quantum noise and the coupling. The full nonlinear dynamics of such an array can become quite involved. Only recently have we produced a full 'phase diagram' of the various patterns to be observed in a 2D array, with stationary and moving spirals and seemingly chaotic patterns.

Marquardt group publications

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4. "Optomechanical cooling of levitated spheres with doubly-resonant fields", G. A. T. Pender, P. F. Barker, Florian Marquardt, J. Millen, and T. S. Monteiro, Phys. Rev. A **85**, 021802(R) (2012)
5. "Enhanced Quantum Nonlinearities in a Two-Mode Optomechanical System", Max Ludwig, Amir H. Safavi-Naeini, Oskar Painter and Florian Marquardt, Phys. Rev. Lett. **109**, 063601 (2012)
6. "Optomechanical circuits for nanomechanical continuous variable quantum state processing", Michael Schmidt, Max Ludwig, and Florian Marquardt, New J. Phys. **14**, 125005 (2012)
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11. "Optomechanically Induced Transparency in the Nonlinear Quantum Regime", Andreas Kronwald and Florian Marquardt, Phys. Rev. Lett. **111**, 133601 (2013)
12. "Arbitrarily large steady-state bosonic squeezing via dissipation", Andreas Kronwald, Florian Marquardt, and Aashish A. Clerk, Phys. Rev. A **88**, 063833 (2013)
13. "Quantum many-body dynamics in optomechanical arrays", Max Ludwig and Florian Marquardt, Phys. Rev. Lett. **111**, 073603 (2013)
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17. "Laser Theory for Optomechanics: Limit Cycles in the Quantum Regime", Niels Lörch, Jiang Qian, Aashish Clerk, Florian Marquardt, and Klemens Hammerer, Phys. Rev. X **4**, 011015 (2014)
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25. "Optomechanical position detection enhanced by de-amplification using intracavity squeezing", V. Peano, H. G. L. Schwefel, Ch. Marquardt, F. Marquardt arXiv:1502.06423 (2015)
26. "Nonlinear radiation pressure dynamics in an optomechanical crystal", Alex G. Krause, Jeff T. Hill, Max Ludwig, Amir H. Safavi-Naeini, Jasper Chan, Florian Marquardt, and Oskar Painter, arXiv:1504.05909 (2015)
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Meystre group highlights

Dissipation-driven two-mode squeezing in optomechanics

- *Dissipation-driven two-mode mechanical squeezed states in optomechanical systems*, Huatang Tan, Gao-xiang Li and P. Meystre, Phys. Rev. A **87**, 033829 (2013).

Quantum squeezing and entanglement have been observed in a number of atomic and photonic systems and are expected to play an increasing role in applications ranging from measurements of feeble forces and fields to quantum information science. For example, it has been know for over three decades, since the pioneering work of V. Braginsky, that squeezed vibrational states are of importance for the measurement beyond the standard quantum limit of the weak signals expected to be produced e.g. in gravitational wave antennas. A new paradigm in quantum state preparation and control has recently received increased attention. Its key aspect is that it exploits *quantum dissipation* in the generation of specific quantum states. Quantum reservoir engineering has been proposed to prepare desirable quantum states. This dissipative approach to quantum state preparation presents the double advantage of being independent of specific initial states and of leading to steady states robust to decoherence.

Based on this general idea we have proposed and analyzed a scheme that exploits cavity dissipation to generate the steady-state two-mode squeezing of two spatially separated mechanical oscillators. These states are also entangled states of continuous variables, a key resource in quantum information processing. We propose specifically two different setups. In the first one two mechanical oscillators are placed inside a two-mode optical resonator, while in the second one the mechanical oscillators are located in two separate single-mode cavities coupled by photon tunneling. The cavities are driven in both cases by amplitude-modulated lasers. In the first model we show analytically that for appropriate mechanical oscillator positions and pump laser parameters the mechanical oscillators can be driven into a stationary two-mode squeezed vacuum by cavity dissipation, provided that mechanical damping is negligible. In the second case a two-step driving sequence can likewise give rise to a steady two-mode mechanical squeezed vacuum state. The effect of thermal fluctuations on the resulting squeezed states is also investigated in detail.

Avoiding parametric instabilities in back-action evading measurements

- *Optomechanical back-action evading measurement without parametric instability,* Steven K. Steinke, P. Meystre, and Keith C. Schwab, Phys. Rev. A **88**, 023838 (2013).

A back-action evading measurement of the position of a membrane in a cavity optomechanical system was proposed as early as 1980 by Braginsky and coworkers, who suggested driving the resonator with an input field resonant with the cavity frequency, but modulated at the mirror frequency. This scheme is often known as two-tone back-action evasion. By modulating the

light field frequency the mirror frequency the measurement effectively turns on and off as the system oscillates. This protocol thereby measures neither position nor momentum individually, but rather, one of the mechanical quadratures. Thus, while measurement back-action only feeds into the unmeasured quadrature and evades the measured one, leaving in principle no lower limit on the uncertainty one quadrature might reach.

While two-tone back-action evasion is an elegant solution, experimental reality intervenes to place a rather restrictive limit on such a scheme. Because the envelope of the driving field oscillates at the mechanical frequency, the intracavity power oscillates at twice the mechanical frequency. Through indirect effects, this leads to the frequency of the mechanical oscillator becoming slightly modulated, with the modulation oscillating at twice the natural frequency. Such a frequency modulation produces a parametric instability that will drive the system and greatly reduce the amount of squeezing possible. To accomplish the back-action evading measurement, high optical power and low mechanical dissipation are both critical, yet these factors both worsen the parametric instability.

However, we have shown that it is in principle possible to work around this particular limitation. There are two critical features needed to avoid the parametric instability while performing the back-action evading measurement: (a) the power in the cavity must not oscillate at twice the mechanical frequency; and (b) the probe light must couple only to a single quadrature of motion. The first of these requirements prevents the instability, and the second prevents measurement back-action from affecting the measured quadrature.
Although the ideal envelope for the intracavity field is a square wave, which satisfies the first criterion above it is sufficient in practice to add a single additional drive tone, which also permits to satisfy the second criterion. Specifically, by simply adding a third tone detuned from the cavity by three times the frequency of the mechanics with appropriate amplitude and phase, one pushes the oscillations in cavity energy to higher harmonics of the mechanical frequency, which in turn do not contribute to the parametric instability. One can then reproduce in the appropriate good-cavity, weak-coupling regime the desired back-action evading measurement of a single mechanical quadrature. Because parametric instabilities appear in very diverse experimental settings, we believe that this modification will prove useful in reaching sub-zero-point position sensitivities deep in the quantum regime.

Quantum optomechanical heat engines

- *A quantum optomechanical heat engine,* Keye Zhang, F. Bariani, and P. Meystre Phys. Rev. Lett. **112**, 150602 (2014).

Quantum heat engines can exhibit intriguing properties, including their potential to outperform their classical analogues. For example, it has been shown that a quantum photo-Carnot engine can extract work from a single reservoir if the latter has built-in quantum coherence, and its power can be increased by noise-induced coherence. In a different situation, a trapped ion

based quantum engine operating on an Otto cycle was shown theoretically to break the Carnot efficiency limit in the presence of a squeezed reservoir.

We have investigated theoretically a quantum optomechanical realization of a *heat engine*. In a generic optomechanical arrangement the optomechanical coupling between the cavity field and the oscillating end mirror results in polariton normal mode excitations whose character depends on the pump detuning and the coupling strength. By varying that detuning it is possible to transform their character from phonon-like to photon-like, so that they are predominantly coupled to the thermal reservoir of phonons or photons, respectively. We exploit the fact that the effective temperatures of these two reservoirs are different to produce an Otto cycle along one of the polariton branches.

We then developed [Ying Dong, Keye Zhang, F. Bariani, and P. Meystre, "Work measurement in an optomechanical quantum heat engine," submitted to Phys. Rev. A] a measurement model to characterize the mean work and its fluctuations in an optomechanical QHE and performed a numerical study of the effect of continuous quantum measurements on its performance. We considered measurement schemes involving the continuous monitoring of the intracavity photon field, with both dispersive and an absorptive interactions with a dilute beam of two-level atoms. By determining the average value and the variance of the work we are able to quantify the measurement back-action effects. In both cases, the measurements were found to induce a reduction in the average work performed by the engine and thus a reduction in its efficiency.

Ongoing work builds further on this idea to consider instead of a heat engine a cavity optomechanical analog of a *heat pump* that uses a polariton fluid to cool mechanical modes coupled to a single pre-cooled phonon mode via external modulation of the substrate of the mechanical resonator. This approach permits to cool phonon modes of frequencies not limited by the cavity-optical field detuning deep into the quantum regime from room temperature.

Meystre group publications

1. G. A. Phelps and P. Meystre, "Laser phase noise effects on the dynamics of optomechanical resonators," Phys. Rev. A **83**, 063838 (2011).
2. H. Jing, D. S. Goldbaum, L. Buchmann, and P. Meystre, "Quantum optomechanics of a Bose-Einstein antiferromagnet," Phys. Rev. Lett. **106**, 223601 (2011).
3. S. Steinke and P. Meystre, "The role of quantum fluctuations in the optomechanical properties of a Bose-Einstein condensate in a ring cavity," Phys. Rev. A **84**, 023834 (2011).
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16. Keye Zhang, P. Meystre, and Weiping Zhang, "Quantum-mechanics-free subsystem in a condensate-based optomechanical setup," Phys. Rev. A **88**, 043632 (2013).
17. Steven K. Steinke, P. Meystre, and Keith C. Schwab, "Optomechanical back-action evading measurement without parametric instability," Phys. Rev. A **88**, 023838 (2013).
18. L. F. Buchmann, E. M. Wright, and P. Meystre, "Phase conjugation in quantum optomechanics," Phys. Rev. A **88**, 041801(R)(Rapid Communication) (2013).

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23. Keye Zhang, F. Bariani, and P. Meystre, “A quantum optomechanical heat engine,” Phys. Rev. Lett. **112**, 150602 (2014).
24. Keye Zhang, F. Bariani, and P. Meystre, “Theory of an optomechanical quantum heat engine,” Phys. Rev. A **90**, 023819 (2014).
25. F. Bariani, S. Singh, L.F. Buchmann, M. Vengalattore, and P. Meystre, “Hybrid optomechanical cooling by atomic systems,” Phys. Rev. A **90**, 033838 (2014).
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27. Keye Zhang, F. Bariani, Y. Dong, Weiping Zhang, and P. Meystre, “A proposed optomechanical microwave sensor at the sub-photon level,” Phys. Rev. Lett. **114**, 113601 (2015).
28. Ying Dong, Keye Zhang, F. Bariani, and P. Meystre, “Work measurement in an optomechanical quantum heat engine”, Phys. Rev. A **92**, 033854 (2015).
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30. Y. Dong, F. Bariani, and P. Meystre, “Phonon cooling cycle by a polariton fluid,” submitted to Phys. Rev. Lett.

Clerk group highlights

Optomechanical quantum state transfer

- *Using interference for high fidelity quantum state transfer in optomechanics*, Y.-D. Wang and A. A. Clerk, Phys. Rev. Lett. **108**, 153603 (2012).
- *Using dark modes for high fidelity optomechanical quantum state transfer*, Y.-D. Wang and A. A. Clerk, New J. Phys. **14**, 105010 (2012).

Among the most promising applications of optomechanics to quantum information processing is the potential to use a mechanical resonance to efficiently transfer a quantum state between two very different physical systems. For example, by coupling a mechanical mode to both a superconducting microwave circuit and an optical cavity, one could transfer a non-classical state of the microwave field (produced by, e.g., a superconducting qubit) to optical photons. This optical state could then be transmitted over great distances. Clearly, having such a quantum interface would be a powerful resource.

In practice, mechanically-mediated state transfer can be severely limited by the dissipation and noise of the mechanical mode. To deal with this problem, we developed a full theory of a new approach to optomechanical quantum state transfer which can be immune to mechanical dissipation. The key insight is that by using suitable choice of drives, one can create a so-called "optomechanical dark mode", a delocalized cavity mode which involves strictly zero mechanical excitation. By adiabatically evolving this mode, an efficient state transfer is completed without being subject to mechanical dissipation. Our work generalizes the well-known STIRAP (Stimulated Raman Adiabatic Passage) procedure of atomic physics to the all-bosonic setting of optomechanics. Aspects of our theory were recently realized in an experiment in the group of ORCHID-funded researcher Hailin Wang [(Dong et al, Science 338, 1609 (2012)].

In further work, we also considered schemes that were in some sense a hybrid between the adiabatic passage technique, and more conventional schemes, where the quantum state of interest is first transferred into the mechanical resonator. Such a "hybrid" approach is much faster than the purely adiabatic scheme, but still yields protection against mechanical loss.

Future work will involve even more detailed theoretical calculations (done in collaboration with experimentalists) to implement these adiabatic transfer ideas in optomechanical crystal systems. It would also be extremely interesting to study generalizations of the "dark-mode" approach in multi-mode optomechanical systems. Here, one will generically have a subspace comprising of multiple independent dark modes, allow in principle a far richer set of mechanically-mediated (but dissipation-protected) quantum operations.

Dissipative quantum state preparation in optomechanics

- *Reservoir-engineered entanglement in optomechanical systems*, Y.-D. Wang and A. A. Clerk, Phys. Rev. Lett. **110**, 253601 (2013).
- *Arbitrary large steady-state bosonic squeezing via dissipation*, A. Kronwald, F. Marquardt and A. A. Clerk, Phys. Rev. A **88**, 063833 (2013).
- *Quantum squeezing of motion in a mechanical resonator,* E. E. Wollman, C. U. Lei, A. J. Weinstein, J. Suh, A. Kronwald, F. Marquardt, A. A. Clerk and K. Schwab, Science **349**, 952 (2015).

Reservoir engineering is an extremely powerful method for generating quantum states. The basic idea is to construct a non-trivial dissipative bath that will relax the system of interest to the desired non-trivial target state; this occurs regardless of the initial system state. Once this initial relaxation occurs, the bath then maintains the system in the desired quantum state at all later times. One has thus stabilized an interesting quantum state, ready for future use in, e.g., a quantum information processing protocol.

We developed theory demonstrating how reservoir engineering could be employed in quantum optomechanical systems, both to prepare non-trivial mechanical states, as well as non-trivial photonic states. These include both squeezed states of motion and light, and entangled states; crucially, our schemes are compatible with the current experimental state-of-the-art. Our protocol for generating quantum squeezed states of mechanical motion was very recently implemented by ORCHID-funded researcher Keith Schwab; a joint theory-experiment paper appeared in Science in 2015.

Future work will involve working closely with experimentalists to implement more of our reservoir-engineering protocols (e.g. the strong entanglement of two mechanical resonators). It would also be extremely interesting to pursue reservoir engineering ideas in regimes where the optomechanical interaction is strong enough to play a role at the single-photon level. In this case, reservoir engineering could be an ideal method for generating non-Gaussian photonic and phononic states.

Dissipative photonic interactions and non-reciprocity in optomechanics

- *Non-reciprocal photon transmission and amplification via reservoir engineering*, A. Metelmann and A. A. Clerk, Phys. Rev. X **5**, 021025 (2015).
- *Quantum-limited amplification via reservoir engineering,* A. Metelmann and A. A. Clerk, Phys. Rev. Lett. **112**, 133904 (2014).

The mechanical degree of freedom in an optomechanical system can be used to induce interactions between photons; in systems having more than one photonic mode, it can make the different modes interact with one another. In certain regimes, the resulting interaction cannot be described by an effective Hamiltonian, as it has an essential dissipative nature. We

developed theory showing that such dissipative interactions could be extremely interesting for various functionalities. Mechanical dissipation could be used to create a new kind of cavity-based photonic quantum-limited amplifier, one which is completely immune to the usual gain-bandwidth limit. Mechanical dissipation can also be used as a new means for constructing non-reciprocal photonic devices; we showed how isolators, circulators and even non-reciprocal quantum limited amplifiers could be implemented optomechanically.

Future work will again focus on implementing these ideas in experiment. We would also like to explore how dissipative non-linear interactions (possible in the strong-interaction limit of optomechanics) could be successfully exploited as a quantum resource.

Clerk group publications

1. “Quantum squeezing of motion in a mechanical resonator”, E. E. Wollman, C. U. Lei, A. J. Weinstein, J. Suh, A. Kronwald, F. Marquardt, A. A. Clerk and K. Schwab, Science **349**, 952 (2015).
2. “Non-reciprocal photon transmission and amplification via reservoir engineering”, A. Metelmann and A. A. Clerk, Phys. Rev. X **5**, 021025 (2015).
3. “Real photons from vacuum fluctuations in optomechanics: role of polariton interactions”, M.-A. Lemonde and A. A. Clerk, Phys. Rev. A **91**, 033836 (2015)**.**
4. “Bipartite and tripartite output entanglement in 3-mode optomechanical systems”, Y. D. Wang, S. Chesi and A. A. Clerk, Phys. Rev. A **91**, 013807 (2015).
5. “Antibunching and unconventional photon blockade with Gaussian squeezed states”, M.-A. Lemonde, N. Didier and A. A. Clerk, Phys. Rev. A **90**, 063824 (2014).
6. “Observation and interpretation of motional sideband asymmetry in a quantum electro-mechanical device”, A. J. Weinstein, C. U. Lei, E. E. Wollman, J. Suh, A. Metelmann, A. A. Clerk, K. C. , Phys. Rev. X **4**, 041003 (2014).
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8. “Dissipative optomechanical squeezing of light”, A. Kronwald, F. Marquardt and A. A. Clerk, New J. Phys. **16**, 063058 (2014).
9. “Mechanical entanglement via detuned parametric amplification”, A. Szorkovszky, A. A. Clerk, A. C. Doherty and W. P. Bowen, New J. Phys. **16**, 063043 (2014).
10. “Two-mode squeezed states in cavity optomechanics via engineering of a single reservoir”, M. J. Woolley and A. A. Clerk, Phys. Rev. A **89**, 063805 (2014).
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12. “Photon propagation in a one-dimensional optomechanical lattice,” W. Chen and A. A. Clerk, Phys. Rev. A **89**, 033854 (2014).
13. “Detuned Mechanical Parametric Amplification as a Quantum Non-Demolition Measurement,” A. Szorkovszky, A. A. Clerk, A. C. Doherty and W. P. Bowen, New J. Phys. **16**, 043023 (2014).
14. "Laser Theory for Optomechanics: Limit Cycles in the Quantum Regime", Niels Lörch, Jiang Qian, Aashish Clerk, Florian Marquardt, and Klemens Hammerer, Phys. Rev. X **4**, 011015 (2014)
15. “Arbitrary large steady-state bosonic squeezing via dissipation”, A. Kronwald, F. Marquardt and A. A. Clerk, Phys. Rev. A **88**, 063833 (2013).
16. “Nonlinear interaction effects in a strongly driven optomechanical cavity”, M.A. Lemonde, N. Didier and A. A. Clerk, Phys. Rev. Lett. **111**, 053602 (2013).
17. “Two-mode backaction evading measurements in cavity optomechanics”, M. Woolley and A. A. Clerk , Phys. Rev. A **87**, 063846 (2013).
18. “Reservoir-engineered entanglement in optomechanical systems”, Y.D. Wang and A. A. Clerk, Phys. Rev. Lett. **110**, 253601 (2013).

19. “Quantum Signatures of the Optomechanical Instability”, J. Qian, A. A. Clerk, K. Hammerer, F. Marquardt, Phys. Rev. Lett. **109**, 253601 (2012).
20. “Using dark modes for high fidelity optomechanical quantum state transfer”, Yingdan Wang and A. A. Clerk, New J. Phys. **14**, 105010 (2012).
21. “Using interference for high fidelity quantum state transfer in optomechanics”, Y.-D. Wang and A. A. Clerk, Phys. Rev. Lett. **108**, 153603 (2012).
22. “Full counting statistics of energy fluctuations in a driven quantum resonator”, A. A. Clerk, Phys. Rev. A **84**, 043824 (2011)

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Grant/Contract Number
AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-10-1-0284

Principal Investigator Name
The full name of the principal investigator on the grant or contract.

Oskar Painter

Program Manager
The AFOSR Program Manager currently assigned to the award

Dr. Tatjana Curcic

Reporting Period Start Date

06/10/2010

Reporting Period End Date

06/09/2015

Abstract

Our efforts within the DARPA/MTO ORCHID program focused on developing and entirely new class of micro- and nano-scale optomechanical devices in which large coupling between light and mechanical motion could be realized via radiation pressure. Application of these devices to mechanical sensors, microwave signal synthesis, and microwave photonics were explored.

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Changes in research objectives (if any):

Change in AFOSR Program Manager, if any:

Extensions granted or milestones slipped, if any:

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

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